(NASA-CR-162318) LUNAR STUDIES Final
Technical Report (Cornell Univ., Ithaca, N.
Y.) 41 p HC A02/MF A01 CSCL 03B

N79-33141

Unclas
G3/91 35849

CORNELL UNIVERSITY

Center for Radiophysics and Space Research

ITHACA, N. Y.

Final Technical Report

to the

National Aeronautics and Space Administration

on

NASA Grant NGL 33-010-005

"Lunar Studies"

Principal Investigator: Professor Thomas Gold

In the period of February 1, 1971 through January 31, 1976 this grant supported our experimental and theoretical research concerning lunar surface processes and the nature, origin and derivation of the lunar surface cover.

The principal research topics involved were:

1. Electrostatic dust motion and transport process

2. Seismological properties of fine rock powders in lunar conditions

3. Surface processes that darken the lunar soil and affect the surface chemical properties of the soil grains

4. Laser simulation of micrometeorite impacts--estimation of the erosion rate caused by the micrometeorite flux

5. The exposure history of the lunar regolith

6. Destruction of amino acids by exposure to a simulation of the solar wind at the lunar surface.

These topics developed from long years of previous studies of lunar processes and analysis of observational data. Some of them involved large-scale experimental research programs. Most of the laboratory observations were first made with rock powders of similar physical and chemical properties as those of lunar material. In the advanced phase of the experimental work, actual lunar material was used in several projects, these were partially sponsored by another NASA grant: NGR 33-010-137.

In this short summary we will point out some of our most important findings. Xerox copies of the abstracts of all the publications resulting from this grant present a more detailed account of our achievements.

Many features on the lunar surface as observed by lunar photography evidenced transport processes of the soil. We had studied a number of possible processes and decided to concentrate on the experimental and theoretical investigation of the electrostatic effects. Experiments in which insulating powders were bombarded with a few hundred eV energy electrons in vacuum were highly successful. Electrostatic agitation of the grains under these conditions produced a great variety of phenomena and interesting surface patterns, very relevant to lunar observations. We explained the observed agitation in terms of differential charging of the neighboring grains and the resulting very intense local electric fields, sufficient to mobilize the dust grains. We conducted a thorough theoretical study of electrostatic dust motion and of its applicability to lunar conditions with very positive results. We also made a systematic investigation of the behavior under electron bombardment of various insulating powders individually and in mixtures. The final phase of this investigation included actual lunar dust samples. A collection of both still photographs and motion pictures of the observed dust motion and of the resulting surface patterns was obtained. The comparison of the laboratory photographs and those of the lunar surface shows striking similarities in a number of cases. We also studied both experimentally and theoretically the combined effects of a U.V. and electron flux and draw conclusions for the lunar case. This work formed the main body of the Ph.D. thesis of G.J. Williams--see the publication list.

Another topic relevant to the nature of the lunar surface cover developed from the discussion of the lunar seismic signals so different from those observed in the Earth. Gold and Soter had shown theoretically how a deep powder layer can give rise to the general features of the lunar signals. We established an experimental program in order to examine whether under lunar conditions rock powders can exhibit the required seismic properties: very low velocities for the acoustic waves and very low attenuation. We measured the longitudinal wave velocity and Q of low frequency acoustic signals in a variety of rock powders. The measurements were made under vacuum using a specially designed and constructed apparatus in our laboratory. We demonstrated that dry, lightly compacted rock powders exhibit very low velocities and high Q and that the velocities increase sharply with compaction. The value of the highest Q measured in the laboratory, when extrapolated to the actual lunar conditions, gave support to the Gold-Soter model.

The explanation of the optical properties of the lunar surface, and in particular its remarkably low albedo, had been a long-standing research topic in our laboratory. We had demonstrated that fine, iron-containing basalt powders, irradiated by 2 keV protons or α particles, in doses equivalent to a few tens of thousands of years of solar wind flux on the lunar surface, approximate well the optical properties of the Moon.

During the years covered by this grant we built an Auger electron spectrometer in our laboratory. With the help of this analytical tool we were able to correlate the surface chemical changes caused by ion bombardment of rock powders with the changes in their optical properties. Most importantly we were able to analyze the surface chemical composition of lunar dust and freshly ground rock samples, the latter representing material unexposed to lunar weathering. We demonstrated a consistent enrichment of iron on the surface of the dust grains relative to the freshly ground rock grains. We also showed a correlation between the albedo of the lunar samples and their surface iron concentration. Indeed the darkest lunar dust samples exhibited the largest surface iron concentration.

We also demonstrated that lunar rock powder samples bombarded with protons or α particles in the laboratory, not only darken but their surface iron concentration increases to the value observed in lunar dust samples. Therefore we were able to give very strong support to the hypothesis that the solar wind is a major factor in altering the surface chemical composition and the albedo of the lunar dust cover. This is an important result for the discussion of the chemical composition of the surface cover of other airless bodies, since most of the available information is from optical observations.

The results of our laser experiments when combined with cosmic ray erosion data on lunar rocks allowed us to estimate the amount of soil moved by micrometeorite "gardening". Our figure agreed within a factor of two with estimates by others based on micrometeorite flux measurements. This strengthened the correspondence between cosmic ray erosion and micrometeorite flux estimates.

Our 3-dimensional model calculations of regolith cratering and exposure indicated that too high a fraction of the grains of an average sample would escape galactic and solar wind exposure, as compared to the observations on lunar samples. The implication of these statistics is that pre-exposure of the grains in space and/or during transit by some orderly process from the uplands is required. This finding of course is very relevant for the discussion of the likelihood of an electrostatic transport process.

We conducted a microscopic and SEM study of the damage patterns on glass beads from the A17 orange soil sample in order to diagnose the nature of the damage-causing event(s). We observed that the beads exhibit an astatistically high prevalence of a single spot of damage rather than none or several such spots. This seemed to evidence damage by an orderly process such as infall of each bead. We designed an experiment involving the impelling of glass beads of size and static crushing strength similar to that of the lunar beads against various targets at various velocities up to ~ 2 km/sec. We hoped to establish reasonably stringent bounds on what the impact velocity of the lunar glass beads must have been. This grant, however, was terminated before this project could be realized.

ABSTRACTS OF PUBLICATIONS RELATING TO THIS GRANT

ELECTROSTATIC TRANSPORTATION OF DUST ON THE MOON

R.J.L. Grard (ed.), Photon and Particle Interaction with Surfaces in Space, 557-560 (1973).

T. GOLD and G. J. WILLIAMS

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Abstract. The study of detailed photography of the lunar surface makes clear that some surface transportation process has been active. Theory and laboratory experiments indicate that electrostatic effects resulting from secondary electron emission are the dominant cause of movement of small grains on the surface. The various electrostatic actions are discussed, and a host of unexpected phenomena are described that have turned up in the course of the laboratory experiments.

AMINO ACID DESTRUCTION UNDER SIMULATED LUNAR CONDITIONS

CRSR 488

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Amino acids, mixed with pulverized olivine basalt similar to the fines in the lunar regolith, have been subjected to lunar regimes of proton irradiation and temperature and to high vacuum. The half-life for the destruction of amino acids mixed to a depth of several cm is ∿ 4000 years, casting doubt on claims that amino acids exist in the lunar regolith.

The Moon 6, 405-413 (1973).

THE SIMULATION OF LUNAR MICROMETEORITE IMPACTS BY LASER PULSES

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Center for Radiophysics and Space Research, Cornell University, Ithaca, N.Y., U.S.A.

(Received 16 February, 1973)

Abstract. Laser pulses of a finely focused beam were used to simulate micrometeorite impacts on lunar rocks and in lunar soil. The electron microscope pictures show the detailed effects so caused; it is possible to derive an estimate of the comparative amounts of erosion a given micrometeorite flux would cause in lunar rocks and lunar soil.

EROSION, TRANSPORTATION AND THE NATURE OF THE MARIA

Proceedings, I.A.U. Symp. No. 47 "The Moon", Newcastle, The Moon (Urey & Runcorn eds.), 55-67 (1972).

T. GOLD
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Abstract. Rock dust appears to have been redistributed over the Moon by effects other than impact explosions. A core sample on Apollo 12 showed sharp and distinctive layers and was clearly unmixed. Surface transportation processes that deposit the dust very gently must have been at work. Orbiter pictures confirm that such surface creep has taken place on a very large scale.

The seismic evidence makes clear that there is no continuous sheet of bedrock at a shallow depth in the vicinity of the Apollo 12 site. A deep deposit of powder would match the seismic properties observed. Mascons require for their explanation a surface transportation process that tends to fill in the large impact basins after their formation.

Surface transportation of lunar dust has been demonstrated in the laboratory to occur most readily as a result of electrostatic forces produced by electron bombardment in the energy range of a few hundred volts. Such bombardment happens on the Moon predominantly when it is in the magnetic tail of the Earth, and this may be the reason why mare ground is so remarkably dominant on the hemispere facing the Earth.

CONJECTURES ABOUT THE EVOLUTION OF THE MOON*

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The Moon 7, 293-306 (1973).

(Received 23 November, 1972)

Abstract. The principal questions about the derivation of the lunar surface have not yet been settled: is it the surface left over from the process of accumulation of the Moon, or is it a surface generated by magmatic processes on the Moon and subsequently altered by further infall from outside? The evidence derived from many sources now favors the former. Seismic data suggest an absence of bedrock down to a depth of several kilometers, and instead a compacted powder only. The 'mascon' evidence can be understood as a consequence of major impacts in a deep porous layer. The great abundance of cosmic ray tracks in most soil samples demands a much greater cosmic ray dosage than present rates would cause in the age of the Moon, unless the dust represented infallen material previously irradiated. The nuclear age, since freezing, of the dust is greater than that of the rocks found. The chemical composition of the dust is not the same as of the rocks. Strict layering of the dust has been seen, implying some process other than meteoritic impacts for its generation and deposition. These and other effects found can be understood in the framework of a cold accumulation description, in which the surface layers represent the last addition of meteoritic infall of a basaltic material similar to, but not identical with the present basaltic achondrites. The possible relation of this material to oceanic basalt on Earth is mentioned.

(Reprinted from Nature, Vol. 240, No. 5382, pp. 458–459, December 22, 1972)

Are the Lunar Seismic Signals compatible with a Deep Layer of Fine Powder?

THE seismic wave velocity may vary with depth in the Moon in the way derived from the lunar seismic signals by Toksöz *et al.*[1]. It is customary to seek sudden changes in velocity and interpret these as evidence for sudden changes in mineral type. Here it is shown that one such sudden change at 25 km and the more gradual increase in velocity from the surface to it can be interpreted in terms of a single type of material, namely the fine rock powder that is so abundant on the lunar surface. Gold and Soter[2] have shown how such a deep powder layer can give rise to the general features of the lunar seismic signals, which are clearly so different from those seen in the Earth.

Good quantitative agreement has been obtained between lunar near surface velocities and values obtained in rock powders in the laboratory[3]. However, Toksöz *et al.*[1] rule out a deep powder layer. They derive a velocity profile for powders from laboratory data on lunar fines[4] by using values of velocity corresponding to the maximum pressure to which the fines were exposed in the laboratory. They thus obtain the result, which we shall see is not necessarily correct, that the depth dependency of velocity in lunar fines would be slower than the actual depth dependency inferred from the seismic signals.

R.J.L. Grard (ed.), Photon and Particle Interactions with Surfaces in Space, 517-519 (1973).

SPUTTERING AND DARKENING OF THE GRAINS ON THE LUNAR SURFACE

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Abstract. Sputtering experiments have been carried out in the lunar laboratory at Cornell (first by B. Hapke) since 1964. These have shown that solar wind exposure will lead to the deposition of a dark layer on grains of most rocks. The nature of this layer is not yet known with certainty, but it is thought to be chiefly due to reduced metals. This confirms the supposition, first put forward in 1955, that the albedo of any part of the lunar surface is dependent on the length of time for which it has been exposed. This albedo effect is likely to dominate over effects due to regional chemical differences.

Proceedings of the Fifth Lunar Conference
(Supplement 5, Geochimica et Cosmochimica Acta)
Vol. 3 pp. 2355–2359 (1974)
Printed in the United States of America

Optical properties of the Apollo 15 deep core samples

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Abstract—The variations of albedo observed at different depths in a core tube show almost as large a range as occurs on the surface over the entire moon. Different regions in the core tube are very sharply separated from each other, demonstrating that little mixing had taken place in the deposition process or subsequently. A possible correlation between albedo and cosmic ray exposure is noted.

Proceedings of the Fifth Lunar Conference
(Supplement 5, Geochimica et Cosmochimica Acta)
Vol. 3 pp. 2413–2422 (1974)
Printed in the United States of America

Observation of iron-rich coating on lunar grains and a relation to low albedo

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Abstract—The outermost few atomic layers of lunar soil samples were studied by Auger spectroscopy and were found to contain in each case two to three times more iron than the mean bulk composition of the sample. The amount of excess iron is found to be closely correlated with the optical albedo in the manner that would be theoretically expected if the iron provided absorption centers. Crushed lunar rocks of similar mean composition, but lacking the extra iron coating of the soil grains, have a much higher albedo than most lunar soils sampled or observed on the lunar surface.

Proceedings of the Third Lunar Science Conference
(Supplement 3, Geochimica et Cosmochimica Acta)
Vol. 3, pp. 2545–2555
The M.I.T. Press, 1972

Measurements of the acoustical parameters of rock powders and the Gold-Soter lunar model

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Abstract—We are measuring the low frequency velocities and damping factors of acoustic waves in rock powders in vacuo with a view to understanding the lunar seismic signals. Our results combined with those of others, when extrapolated to lunar conditions, lend support to the Gold-Soter model of the outer moon in which the lunar surface is covered with a fine rock powder to a depth of at least 4 km.

VOL. 78, NO. 23 JOURNAL OF GEOPHYSICAL RESEARCH AUGUST 10, 1973

Seismic Properties of Fine Rock Powders in Lunar Conditions

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Seismic properties of fine rock powders in near lunar surface conditions have been measured in the laboratory, and they correspond well with those obtained for the near lunar surface. The laboratory values of Q range from 40 to 330 with corresponding wave velocities c_l below 100 m/s. Many of the results obtained are shown to be understandable in terms of current theories of the elastic and plastic properties of fine rock powders in a variety of temperature and pressure conditions. This enables some estimate to be made of the changes in Q and c_l with depth in the moon, on the supposition that fine rock powder continues downward as an abundant constituent.

J. Phys D: Appl. Phys., Vol. 7, 1974. Printed in Great Britain.

Grain–grain contact geometry and the propagation of elastic waves in granular media

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Received 12 February 1973, in final form 6 November 1973

Abstract. It is shown that the compliance of an orthogonal grain-grain contact is so insensitive to the grain geometry in the contact region that this geometry is not at present an important parameter in theories of the speed of propagation of elastic waves in granular media, such as occur in the Earth and in the Moon.

THE MOVEMENT OF SMALL PARTICULATE MATTER IN THE EARLY SOLAR SYSTEM AND THE FORMATION OF SATELLITES

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(Read by E. E. Salpeter)

Satellites are a common feature in the solar system, and all planets on which satellite orbits would be stable possess them. (For Mercury the solar perturbation is too large, and the retrograde spin of Venus would cause satellites to spiral in to the planet through tidal friction.) An explanation of the formation of satellites must hence be one which makes the phenomenon exceedingly probable at some stage in the solar system formation processes, and very improbable processes like a capture cannot be the answer in most cases.

Small particulate matter must have been very abundant in the early solar nebula. Such particulate matter must have existed both from the first condensation of the low vapor pressure components of the gas in the first round, and it must also have been composed of material scattered from impacts after some major bodies had begun to form, frequently finding themselves no doubt on collision orbits.

In general, small particulate matter will not follow the same orbits as large bodies would, due to the action of drag forces. In the early solar system such drag must have been present within the original gaseous disc, and at later stages there continued to be a slight drag due to the Poynting-Robertson effect. The gas drag, depending on the mass and temperature distribution of the gas in the early solar nebula, could have acted to supply a force on small particles, either in the forward direction of planetary orbits, or in the retrograde direction. Particles could thus be caused to spiral either outwards or inwards, as a result of such forces.

Such material will frequently not continue to move on a spiral orbit, for it will frequently happen that, as the mean period gradually changes, a particle comes into resonance with a perturbing force arising from the motion of major bodies. Such resonances can be of two kinds: one causing stability for that particular period, the other removing material even more quickly from orbits of that period than the spiral motion would have done. In the one location in the solar system where we still see small particulate matter on long-lived orbits, we indeed see the material organized into well-defined rings, namely the rings of Saturn. It may well be that even at the present time there exists a similar banded structure for particles of a certain size range in the plane of the solar system, with some bands as a result of planetary perturbations having permanent stability, despite the Poynting-Robertson effect. The zodiacal light may be due to a set of bands that would make the solar system look like a faint version of Saturn's rings when viewed from outside the central plane.

Contopoulos (ed.), Highlights of Astronomy, 483–485.

Such bands will have been a most important feature in the condensation processes in earlier times. It is in these circumstances, where a nonconservative force has been active, that Liouville's theorem is not satisfied, and indeed particles will be driven into much higher densities than the densities at which they were originally supplied. It is important to realize that the process will also sort particles for a certain size range, in the sense that the ones that are too small (for the strength of any particular celestial mechanics resonance) cannot be arrested against the drag force that causes spiraling, while particles that are too large may spiral so slowly as not to reach a resonant condition. A resonant band will thus first be supplied with the smallest particles that can be stable in that resonance and will later gradually acquire larger and larger objects. The relative velocities, and thus the erosion rates through mutual collisions, will become very small, and the circumstances will be favorable for snowballing, to make larger particles with the help of any surface stiction. The concentration of asteroids into the Trojan orbits cannot readily be understood without such an action. It is also important to realize that such lanes may in some cases have been supplied principally from original condensate, but in other cases from debris of collisions of earlier bodies. Different lanes may thus be chemically and mineralogically distinctive. In the course of long times, the stability of individual planetary bands may be lost as a result of various changes. Major perturbations among the planets, further accretion, or major collision, could so change the celestial mechanics situation as to destroy the resonance with a particular band, and it would then again begin to spiral. Now, however, the starting point would be an enormously more concentrated, narrow lane of highly collimated orbits, rather than a diffuse distribution in the whole disc. The densities of particulate matter in such a band may well have risen above the mean by a factor of the order of 10^4. We must then visualize that there will have been many events of such highly concentrated bands becoming unlocked from their resonance and therefore spiraling in the solar system. When such material reaches the vicinity of a planet each particle may suffer one of three possible fates. Firstly it may impact the planet and thus contribute to its growth. Secondly it may, after a period of large perturbations, cross safely to the other side of the sphere of influence of that planet and then continue with its spiral. Thirdly, it may be placed on a satellite orbit to that planet, a probability which would be greatly increased by the presence of a frictional medium such as the main solar nebula, or its temporary concentration in the vicinity of the planets. It is extremely difficult to make any estimate of the relative probability of the three types of encounter. Even if the setting up of a satellite orbit were many times less probable than the other two possibilities, it would still suffice to lead to the eventual formation of the satellites that we know, if the process occurred early enough so that a large proportion could still be added to make the planets grow.

The step from circumplanetary rings attenuated by gas friction to the formation of satellite bodies is not a difficult one and has been discussed on many occasions. If in the first place a number of separate satellites form, as may well be the rule, it will depend on their size distribution, and the tidal friction with the planet, whether they can be maintained as separate bodies. If tidal friction is sufficient and there is forward spinning planet, and if the innermost satellite formed is more massive than the others, then they will all be swept up into one body finally. This is because the most massive satellite will spiral out the fastest, and there is no possibility in this case of one body crossing the lane of the next without colliding with it. Perhaps this is the set of events that occurred to make our rather large Moon, while in the case of the major planets the evolution through tidal friction has been somewhat slower. The material that now forms the surface of the Moon is perhaps the last addition, and the soil that is found there is material acquired directly in its present form from orbit. The fact that the material has suffered chemical differentiation on a planetary body in its past does not argue against such a theory. As we have said, many of the bands will be debris from collisions, and the last material acquired by the Moon may be one of those. Whatever finely divided material fell into the Moon in the late phases would tend to make a set of layers that may be chemically distinctive. Any of the larger impacts, such as those that caused the mare basins, must then rework the layered structure into one that makes for regional differences in composition. Much detail that is now known about the lunar soil is difficult if not impossible to account for within the view that this soil resulted from the grinding up by meteorite bombardment of solid lunar rocks. In particular, the high intensity and remarkable uniformity of the cosmic ray exposure of all the soil seems to accord much better with a picture in which this soil was in diffuse form in orbit and fell in to make the last addition to the Moon. (The impact on collision of each grain with the lunar surface would not heat the particles enough to eradicate the cosmic ray tracks if infall was from other Earth satellite orbits only.)

The recent radar observations from the Jet Propulsion Laboratory at Goldstone of Saturn's rings suggest that they are made largely of metallic particles. (The alternative theory that they are made of dielectric material in accurately spherical form – cat's eyes – is considered unlikely, since we know of no mechanism that would tend to assemble meter-sized spheres as would be required.) This observation emphasizes the view that bands of particular composition can be formed and become placed on satellite orbits. The rings of Saturn are too close to the planet to form further satellites, but the greatly varying composition of the satellites suggests that similar processes had occurred there but with differently sorted out, second generation debris material.

Acknowledgement

Work on lunar studies is carried out under NASA Grant NGL-33-010-005.

from Lunar Science V; Lunar Science Institute, Houston (1974)

ELECTROSTATIC EFFECTS ON THE LUNAR SURFACE, T. Gold and G. J. Williams, Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14850.

The large scale electric fields around the Moon and the mean charges of surface grains of the soil can readily be seen to result in forces that are much too small to cause any movement of grains. However there are effects that are expected in the environment of the Moon, where the charge on neighboring grains is quite dissimilar, and where electric fields are set up on a micron-scale. In such circumstances the forces on a grain may well exceed not only gravity but also the adhesive force to the neighbors that are in contact. Surface movement then results and may cause surface transportation of lunar soil on a geologically important scale.

We report here the laboratory experimentation and the theoretical investigation of the effects that set up such intense small scale fields. UV photons from the Sun, the solar wind, and the plasma bombardment in the wake of the Earth all need to be considered. While photon-produced electrostatic effects are not large, they may cause some movement of surface grains on the Moon. The free-stream solar wind has only negligible effects. The electrons that reach energies of several hundred volts in the region behind the Earth's magnetic bow-shock seem the most effective agency for causing surface movement, and such movement caused by locally unstable electron charging is readily demonstrated in the laboratory.

Photoelectrons are very numerous compared with the more energetic electrons of the magnetosheath. It might be thought that their action would be to destroy all the intense small-scale electric fields, and to bring potential differences down to the few volt range of the photoelectrons. This is, however, not so. All localities in the complex surface geometry that can receive electrons from the wide-angle electron bombardment, but not photons from the narrow-angle solar illumination and that charge up negatively cannot be discharged by photoelectrons. A large fraction of the surface grains at any time are in that situation, and therefore electron bombardment effects are expected to be not greatly diminished by the presence of the solar UV.

Magnetosheath electron bombardment provides an explanation for the great difference in the appearance and surface topography between the back and the front of the Moon, if indeed surface erosion by such effects has played a major part in shaping the surface.

ELECTROSTATIC EFFECTS ON THE LUNAR SURFACE

T. Gold and G. J. Williams

Various interesting effects are noted in the laboratory tests. Such as the sorting of grains according to some features of their chemical composition that influence their secondary emission characteristics, and the impediment to transportation caused by a mixture of certain substances. These effects provide explanations for various seemingly strange properties of the lunar surface that have been noted.

Proceedings of the Fifth Lunar Conference
(Supplement 5, Geochimica et Cosmochimica Acta)
Vol. 3 pp. 2387–2395 (1974)
Printed in the United States of America

On the exposure history of the lunar regolith

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Abstract—The observed minimum and mean values of track densities in lunar grains are both found to exceed the values expected from exposure with redistribution by vertical mixing, and the percentage of the smaller grains showing very high track densities is too large by a factor of more than ten. Previous exposure of the material (in space before accretion onto the moon or in regions from which net migration has occurred) may be necessitated.

ICARUS 24, 134–135 (1975)

Remarks on the Paper "The Tidal Loss of Satellite-Orbiting Objects and Its Implications for the Lunar Surface" by Mark J. Reid

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Received December 20, 1973; revised August 9, 1974

The paper by Reid suggests that masses may be stored in circumlunar orbits for long periods of time, limited only by tidal dissipation. The real loss may, however, be much faster, due to large changes in the orbit caused by the disturbing field of the Earth. It is shown that the example quoted of Jupiter's satellites is inadequate to make the case for stability of such orbits.

Proc. Lunar Sci. Conf. 6th (1975), p. 3285–3303.
Printed in the United States of America

Auger analysis of the lunar soil: Study of processes which change the surface chemistry and albedo

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Abstract—The chemical composition of the outermost few atomic layers of thirteen soil samples and six rock samples from all Apollo sites was studied by Auger electron spectroscopy. All soil samples showed a large increase in the iron-to-oxygen ratio (and thereby of the surface concentration of iron) compared with samples of crushed rock or with results of the bulk chemical analysis. The negative correlation between the amount of this enhanced iron and the albedo of soil samples, reported earlier by us, is now greatly strengthened, and shows the functional dependence expected from a population of absorption centers that is proportional to the surface iron content.

Crushed lunar rock samples exposed to 2-keV protons that simulate solar-wind exposure for 2000–3000 yr exhibit both an increase of the surface iron and a lowering of the albedo that makes these resemble closely the lunar soil in both respects. While a variety of surface modification effects may have been present, it appears that an adequate explanation for the low albedo of the moon and the chemical surface properties of the soil can be found in the selective depletion of oxygen (and other light elements) by solar wind sputtering.

from Lunar Science VI, Part I, Lunar Science Institute, Houston, 1975

EXTRALUNAR ORIGIN OF THE LUNAR SOIL. T. Gold, Center for Radiophysics & Space Research, Cornell Univ., Ithaca, N.Y. 14850

The possibility that the lunar surface represents merely the last stages of the accretion process that formed the Moon has not received much attention (1,2,3). Yet, this is clearly a question of overriding importance to the entire lunar investigation program.

Very strong evidence concerning the lunar soil, such as its exposure record, its state of deposition, as well as radar and seismic evidence, now appears to us to make the case that the surface material fell in more or less in its present form, rather than that it is the consequence of meteoritic grinding of a lunar endogenic crust. Further evidence concerning the Apollo 17 orange soil, the mascons and their absence on the back, and the many indications of surface denudation and deposition all speak for infall and surface transportation processes as having been the dominant effects.

Many investigators believe that the chemical evidence has proved the opposite case, namely that a chemical differentiation history on the Moon must have preceded the production of the present soil. That these differentiation processes occurred in the material that came to form the lunar soil cannot be doubted. However, there is no way of knowing where this happened. So long as we have no clear understanding of the origin of the Moon, any assumption concerning the original nature of the material must be a weak and needlessly restrictive one.

It has been claimed that the lunar chemical analysis has shown the material to represent to some extent a closed chemical system. This claim can be doubted, but in any case it would not affect the present debate, since the same considerations of chemistry can be applied to a previous body whose surface material may have become the dominant contribution to the outer few kilometers of the Moon.

Nor can the regional distribution be taken to prove that case. It is clear that a large amount of vertical redistribution has taken place on the Moon, such as the deep excavations of the great basins and the deposition of that material to form the surrounding mountains. Therefore any vertical differences, resulting from a compositional change in the course of the accretion, will exhibit themselves as regional differences now. Denudation of high ground keeps exhibiting the lower material there (and crater profiles show that generally more than 2 km have been removed), while the last addition must dominate on the flat low ground. Thus differences among successive layers of the accreted material tend to show themselves as differences between high and low ground.

The lunar soil shows generally a remarkably high surface exposure, as judged by its cosmic ray tracks, by its implanted gases, and by its surface sputter or condensation deposited layer. If this degree of surface exposure occurred during the entire age of the Moon at the present rate, only a thin layer could have been treated, however well the material was stirred or moved. The estimates of the maximum amount so treated range from a few tens of centimeters to a few meters. While this may perhaps seem adequate to account for the material investigated in the form of the three meter drill

EXTRALUNAR ORIGIN OF LUNAR SOIL

Gold, T.

cores, it is far from adequate when the stirring by larger crater forming events is taken into account. Much of the material now in the top few meters must have come from nearby craters that are many tens of meters deep. A substantial admixture of unexposed material should therefore be present almost everywhere in the soil.

Apart from the total amount of surface exposure, the distribution also cannot be accounted for. If random stirring were held responsible for bringing grains to the surface for exposure, then even the most vigorous stirring would still give a much larger proportion of unexposed grains than is found. A computer simulation study (4,5) demonstrates this clearly.

Furthermore, most of the core tubes investigated show many very distinctive layers, with differences of grain size, albedo and chemical composition. However these layers might be produced, their presence argues against the supposition that the soil has generally been stirred exceedingly thoroughly so that most grains could acquire their surface exposure.

If on the other hand direct infall were responsible for the soil, then the observed exposure record would refer to both the exposure suffered by a grain before and after landing on the Moon. Exposure of a tenuous cloud of grains would then be needed only for a short time, on account of the much greater surface area presented; each grain in the cloud may receive an exposure rate as high as only the uppermost layer does on the Moon. Infall of small grains onto a surface that is itself composed of loosely packed small grains will not eradicate either cosmic ray tracks by heat annealing or destroy surface deposits, so long as the infall speeds are only of the order of the escape speed of the Moon (2.4 km/sec). In fact, planetary accretion processes may well supply grains out of gradually attenuating orbits, and the impact speed would then be as low as 1.7 km/sec (the lunar orbital velocity), assuring the almost complete preservation of all details of the grains.

The Apollo 17 orange soil demonstrates a history of having been frozen from melt in space, and then, as completely hard particles--mainly small spheres or spheroids--having impacted the surface. Electron microscopy studies, performed in our laboratories, on a large number of beads show them to exhibit a very uniform degree of damage; the large beads have mostly one large area of damage on them, and the small ones have a small area of damage. In contrast with most rock chips there appear no hypervelocity impact craters on any of this material. Detailed statistics show that the damage observed must be almost entirely the one resulting from the infall of the material itself, not from any subsequent bombardment. Measurements of the breaking strength of the beads indicate that a high speed of impact into the soft lunar soil would have been required to cause the observed degree of damage; a speed of 1.7 km/sec, the lunar orbital speed, seems to be inadequate. Pending experimental results with glass beads of similar strength, shot into lunar surface type of material, one can only make approximate calculations to define the speed these objects must have had. Our estimates suggest a speed be ween 3 and 4 km/sec, well above the orbital speed. In that case this material was part of an infall, and not merely distributed from another location on the Moon. In any case the fall must have covered a large area, possibly the entire Moon, and the small patch found is the consequence of

EXTRALUNAR ORIGIN OF LUNAR SOIL

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other processes having preserved it unmixed and having brought it to the surface in this location (as well as many others, perhaps, that the astronauts did not happen to visit). The material, though chemically distinctive from most of the lunar material, is nevertheless of a lunar type of composition so far as many abundance ratios are concerned. If it came into the Moon at more than orbital speed and hence from a non-lunar source, the presumption must be that the rest of the soil, being chemically similar, also came from that source. The orange soil thus provides an extremely useful sample of lunar soil for the deduction whether it all is of lunar or extra-lunar origin.

The various radar observations and the seismic measurements combine to show the absence of any discontinuity to a general layer of higher density underlying the soil at a shallow depth, but are compatible with a soil that gradually gets more compacted with depth in addition to local variations of compaction. This is the situation that would be expected from the infall of powder as well as larger bodies. The largest impacts will have left liquefied rock and this may well be the origin of the crystalline rocks, later scattered by smaller impacts. Soil being an older constituent than the rocks would fit in well with nuclear age dating.

The lunar gravity anomalies called "mascons" have a ready explanation if surface flows have tended to raise the floor level of low areas previously hydrostatically balanced. Where no such surface flows occurred there should be no mascons. Where a large impact had left a pattern of concentric rings and valleys the gravity map should merely reflect these remaining departures from equilibrium--just as is the case in Mare Orientale--while any subsequent addition of material by surface flow would generate a positive gravity anomaly. On this basis the depressions on the back of the Moon, being unfilled, should represent no gravity anomalies. This appears now to have been observed.

The suggestion that the presence of lava on the front side facilitated the generation of mascons would imply that the more fluid face produced the larger amounts of hydrostatic imbalance--a most unlikely conclusion.

Lastly, the extreme similarity of the surface of Mercury to that of the Moon suggests that no complex interplay of internal and external activity should be invoked, for it would be most unlikely to have been so similar for two bodies that are internally so different. There is no problem if this is the appearance of a surface generated by infall and the common external effects.

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REGOLITH STIRRING AND EXPOSURE: 3-DIMENSIONAL STUDY,
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Intro. Lunar soil samples apparently have experienced exposure to cosmic rays (galactic and/or solar) through some remarkably orderly process. That is to say, soil samples showing exposure contain very few -- if any -- unexposed grains. The uniformity with which each grain in the sample has received at least some exposure is an important datum. It can be used to assess various proposed histories of the lunar material. This paper presents the results of a three-dimensional computer simulation of regolith exposure. Excavation and mixing of the soil according to the cratering frequency law of Shoemaker et al.(1) is employed. The results confirm the indications of the earlier one-dimensional study(2) -- exposure in situ, with churning by meteorites, is insufficient to explain the notable extent to which unexposed grains are absent.

Cosmic-ray penetration depths The galactic cosmic-ray flux is attenuated, at a depth of about 64 cm, by a factor of ~ 1000 with respect to the flux received in the top 10 cm or so of the soil (3). Solar cosmic rays are of lower energy and have an effective penetration depth of less than 1 cm. (Lunar soil samples commonly have been obtained, by core tubes, from depths of about 2 meters or more. Two meters is more than 3 times the maximum depth at which significant exposure can occur.)

Review of observed cosmic-ray track density distributions
Typically, 95% of the grains in soil samples readily reveal a substantial track density (4).* The minimum track density of grains in this 95% is about (1/1000) or more of the mean grain track density seen in the sample (3). Observation of tracks in the remaining 5% of the grains is more difficult. However, use of special techniques (particularly ones involving electron microscopy) has revealed comparable levels of exposure in most of the remaining 5%.**The percentage of a typical sample's grains for which exposure remains to be established is only 1 or 2%. That is, the fraction of unexposed grains (in samples showing exposure)*** may be zero; the most stringent upper limit which

*(This figure, of course, excludes the glass component of samples. Retention of etchable tracks in glass is known to be poor.)

**(Grains which required special techniques in order for tracks to be observable were found to exhibit slip dislocations which broke the tracks into short segments, making observation difficult(4). Distortion and/or annealling of some of the grains by impacts is in any case to be expected.)

***(The proviso "in samples showing exposure" refers to the possibility of a sample showing no tracks. The latter could result from annealling of the sample,by heat or shock, in impact events.)

can be set currently is about 1 or 2% (4).

The three-dimensional calculation A computer was used to perform a Monte-Carlo simulation of regolith exposure accompanied by cratering. It was assumed that the meteorite flux, whatever its absolute value may have been, had the form(1): $F(c) \propto c^{-2.93}$. F is the flux of meteorites causing craters of diameter greater than or equal to c. (Small-scale excavations occur more frequently than large-scale excavations.) The conclusions of the study are not very sensitive to the crater production law assumed. The aspect ratio b of the craters (ratio of diameter to depth) was taken to be a single constant for craters of all sizes. A value for b was not chosen; it does not enter when one merely specifies that tilling by meteorites has reached to a certain median depth. Craters of square aperture and vertical sides were chosen for simplicity. The excavated material was taken to be deposited in a blanket of uniform thickness and square border surrounding the crater. (See Figure 1.) The ratio η of ejecta blanket thickness to crater depth was taken to be independent of crater depth. The value of η in the basic calculation was chosen to be 1/8, for reasons of computational tractability. The results can be scaled for other values of η.

Each event excavates material which thereupon becomes arrayed in a thin blanket. At each time-step, one unit of aging is accorded to all material within a certain depth beneath the surface. (One time-step is the time-constant for an impact or impacts to create a single excavation of minimum depth.) Compounding of statistics was employed to deal with the effects of successively smaller-scale classes of cratering events. The material was dealt with in the form of distribution functions, rather than following a limited number of grains. We define N(0) to be the fraction of a sample's material which has never resided within an exposure-length λ beneath the surface. The dependence of N(0) upon η can be shown to be: $N(0) \propto \eta^{\gamma}$, where γ is a positive number less than 1.0. Care was taken that all approximations have the effect of underestimating N(0) rather than overestimating it.

As tilling proceeds, N(0) would be diminished rapidly were it not for the fact that the greatest depth to which cratering has occurred will increase, on average, linearly with the number of time-steps. Admixture of previously unprocessed material from beneath is unavoidable in the actual case and was artificially excluded in the theoretical simulation to less an extent than in the calculations of others (e.g.,(3).) The deeper excavations continually spoil what might otherwise have been a distribution with no unexposed grains. N(0) decreases with time initially. Thereafter, there is an approach to what is essentially a steady state.

REGOLITH STIRRING AND EXPOSURE

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Results of the three-dimensional calculation The calculation yielded the distributions $N(L_{Tilled}, L, E_\lambda)$ in amount of time E_λ spent within an exposure-depth λ beneath the surface. L is the depth at which the soil sample is found. L_{Tilled} is the median depth to which tilling of the regolith proceeded. It is, of course, the distribution in relative degree of exposure which is of import and, most simply, one may consider the fraction $N(L_{Tilled}, L, 0)$ which has never experienced residence within the depth λ beneath the surface.

Typical results are shown in Figure 2. We reiterate that the zero- and low-exposure end of the histograms represents an underestimation.

Conclusions It can be seen from the theoretical results that in-situ meteoritic tilling fails to explain the remarkable extent to which unexposed grains are absent from the majority of lunar soil samples. From the upper limit to the observed value of N(0) and from the form of the dependence upon η, we have that the ejecta-blanket thickness factor η may be significantly smaller than 1/200 without invalidating the conclusions of this study. The results indicate that pre-exposure in space (and/or during transit by some orderly process from the uplands) is required for the bulk of the lunar soil.

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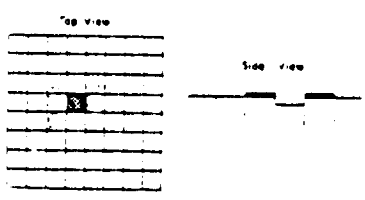

Fig. 1

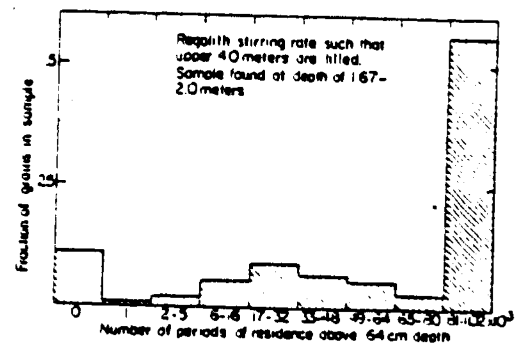

Fig. 2

Fig. 1. Model. Cratering events throw out blankets of ejecta.

Fig. 2. Time spent within a cosmic-ray exposure depth is recorded. A large number of unexposed grains is seen to result.

Proc. Lunar Sci. Conf. 7th (1976), p. 901-911.
Printed in the United States of America

The surface chemical composition of lunar samples and its significance for optical properties

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Abstract—The surface iron, titanium, calcium, and silicon concentration in numerous lunar soil and rock samples was determined by Auger electron spectroscopy. As reported previously all soil samples show a large increase in the iron to oxygen ratio (and thereby of the surface concentration of iron) compared with samples of pulverized rock or with results of their bulk chemical analysis. The surface titanium concentration of the soil is also significantly increased vs. the bulk concentration whereas the surface calcium and silicon concentration is not significantly different from the bulk concentration in these elements.

A solar wind simulation experiment using 2 keV energy α-particles showed that an ion dose corresponding to approximately 30,000 yr of solar wind increased the iron concentration on the surface of the pulverized Apollo 14 rock sample, 14310 to the concentration measured in the Apollo 14 soil sample 14163 *and* the albedo of the pulverized rock decreased from 0.36 to 0.07.

The low albedo (as compared to that of pulverized rock) of the lunar soil is seen to be closely in step with the surface concentration of iron and titanium as determined by Auger methods. A solar wind sputter reduction mechanism is discussed as a possible cause for both the surface chemical and optical properties of the soil.

VOL. 82, NO. 30 JOURNAL OF GEOPHYSICAL RESEARCH OCTOBER 10, 1977

The Search For the Cause of the Low Albedo of The Moon

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The effects of different weathering processes on the albedo of the lunar surface cover is discussed. The surface chemical composition of numerous lunar soil and pulverized rock samples was determined by auger electron spectroscopy. The optical albedo of these samples was also measured. The chemical concentration of iron and titanium is greater on the surface of soil samples than it is on the surface of crushed rock samples with similar bulk composition, whereas the albedo of soil samples is lower than that of the crushed rock samples. A correlation is presented between the surface iron + titanium content and the albedo. Results of solar wind simulation experiments show that irradiation of crushed lunar rock samples with a small dose (corresponding to 3000 years of solar wind) of 2-keV energy protons changed the surface chemistry of the rock to that of the soil. A much larger dose of protons (corresponding to 30,000 years of solar wind) was needed to darken crushed rock to the albedo of the soil of similar bulk chemical composition. The mechanism of darkening by solar wind is discussed, and its effectiveness is compared to that of other darkening processes.

Phil. Trans. R. Soc. Lond. A. **285**, 427–431 (1977) [427]
Printed in Great Britain

The relationship of surface chemistry and albedo of lunar soil samples

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A relation between the albedo and the surface iron concentration (determined by Auger electron spectroscopy) of lunar soil samples is described. The effect of solar wind sputtering on the surface chemistry and albedo of the soil is discussed.

Phil. Trans. R. Soc. Lond. A. **285**, 555–559 (1977) [555]
Printed in Great Britain

Origin and evolution of the lunar surface: the major questions remaining

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The major factors in the evolution of the lunar surface have not been determined yet. Huge lava flows and lunar differentiation, though commonly assumed, is in discord with much of the evidence. The alternative is for most of the surface to represent the last stages of accretion of the Moon only, with the chemical differentiation having taken place previously in the source material. Radar, seismic, surface exposure, and mascon evidence can then be accounted for. A large-scale surface transport mechanism of soil must then have been present.

ELECTRODYNAMICS AND THE MOON -- TRANSPORT PROCESSES

Gregory John Williams, Ph.D.
Cornell University 1976

Part A (Electrostatic Transport Effects on the Lunar Surface)

There is evidence that the rock powder that largely covers the lunar surface has suffered some transportation over geologic times by means other than the blasting of meteoritic impacts. In the absence of an atmosphere, electrical forces acting on small grains may be a major effect causing surface movements. Laboratory experiments have demonstrated that under certain circumstances of electron bombardment insulating powders develop surface agitation leading to a flow. The strongest such effects are due to instabilities in the charging of individual grains, leading to markedly different potentials of neighboring grains and large electrostatic forces between them.

The various electrical charging effects likely to occur on the lunar surface in the presence of solar wind and solar photon bombardment are discussed herein, with particular interest in the circumstances that cause intense microscopic electric fields. It appears that the partially thermalized solar wind in the magnetosheath of the Earth is particularly favorable in this respect, and large changes on the Moon may have been caused by this in geologic time.

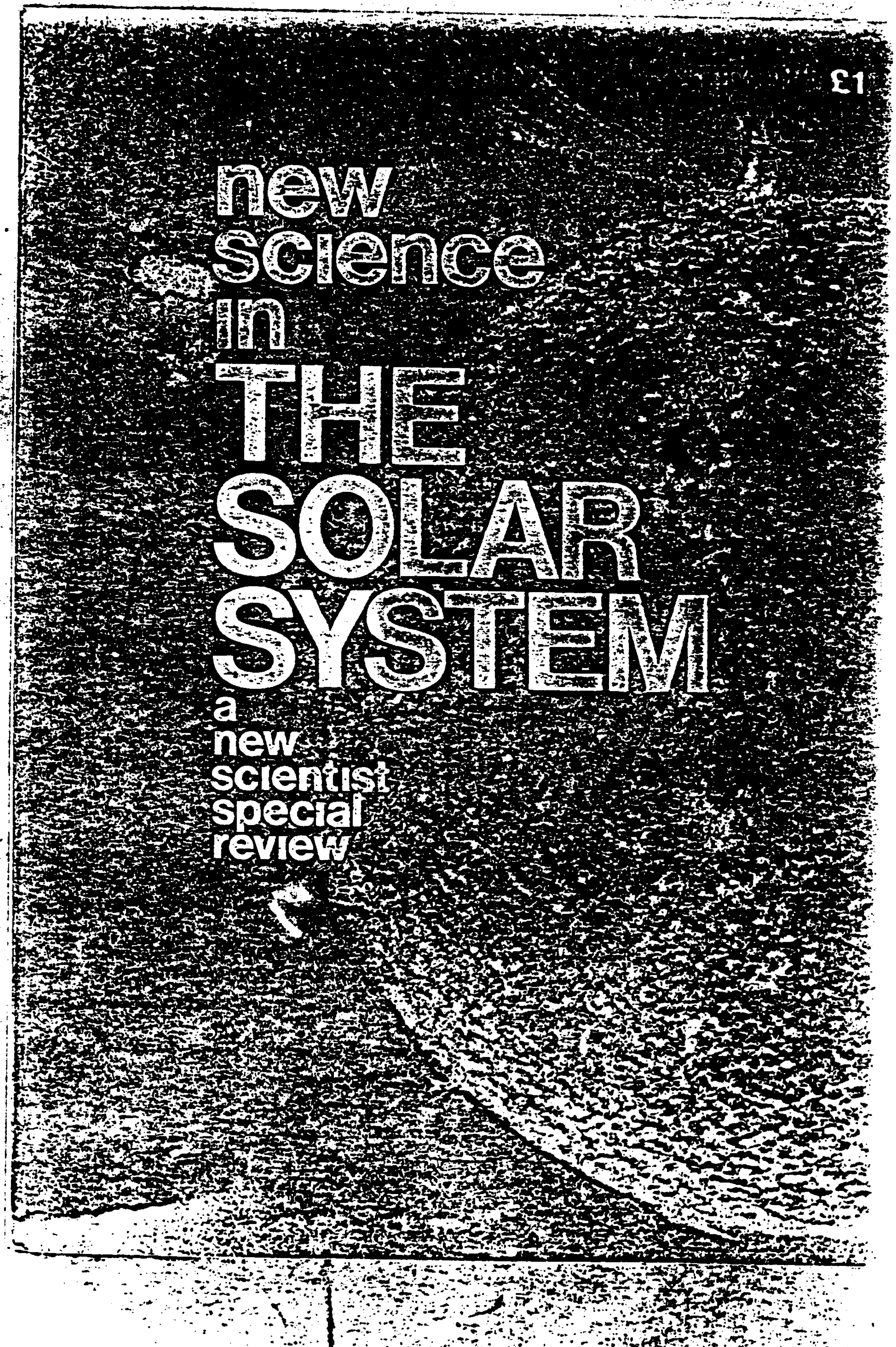
Since the magnetosheath of the Earth will cause the front of the Moon to be treated very differently from the back, one may seek the origin of the striking differences between these two hemispheres in such effects.

It is shown that grain migration can be impeded at the line of contact with a dissimilar powder. Thick beds of accumulated powder, with a sharply defined flow-front, may result. Thus, one can have regional differences in composition despite occurrence of a large amount of grain migration.

Part B (Statistical and Physical Considerations Concerning the Origin and Evolution of the Lunar Surface Materials -- Implications of the Exposure Records)

The potential of the various types of exposure data for discriminating between proposed histories of the lunar surface material is assessed. Redistribution of material by meteorite impact is considered. The results of a calculation which models exposure accompanied by meteoritic tilling are presented. The galactic cosmic ray track density distributions for the sampled lunar materials are found to be explicable in terms of a bombardment-dominated evolution of the surface materials -- with the following important reservations. An orderly, additional process of exposure such that each grain acquires at least the minimum observed galactic cosmic ray track density is admissible and may be required for the mare material. (Were material with galactic cosmic ray track density less than 1×10^5 tracks/cm^2 present in the maria, there would be a probability of only 25% or less that the sampling performed there would have failed to encounter it.) The second point of concern is that the great range of galactic cosmic ray track densities observed to be present within almost all soil samples implies that homogenization over a substantial depth scale -- ten to fifteen centimeters -- has generally occurred. It is not yet clear that this degree of intermingling of particle trajectories is in good quantitative accord with the frequency of occurrence of sharply delineated layers of anomalous composition. Grain-by-grain transport at a rate competitive with meteoritic tilling may be necessary to create (and/or to preserve, by covering) such layers.

The limits (set by exposure data) upon the extent to which grain-by-grain, non-meteoritic transport or accumulation processes can have operated in the later stages of lunar history are discussed. Very rapid transport (grain migration resulting in accumulation of material in the maria) earlier in the history of the Moon, with subsequent transport occurring at smaller rates, is one clear possibility. One could, for example, have it that the mare basins were filled by grain migration in the first 1 to 3×10^9 years; a declining rate of transport would have allowed meteoritic tilling to increase in relative importance with time.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represent such a supercontinent; and the much smoother northern hemisphere, a primordial waterless Martian "ocean"?

Weather satellites have given us the first overall pictures of Earth's weather systems on a large scale; and are now paving the way to total monitoring of atmospheric convolutions, and temperature, pressure and humidity changes. Other satellites orbiting the Earth have told us a lot of new things about the ionosphere and upper atmosphere — especially about chemical composition, ion and electron densities and temperatures, and the daily variation of all these factors as the Earth's rotation switches the solar radiation on and off and varies the degree of ionisation, say, or the altitudes at which certain phenomena occur. Still higher satellites have provided a comprehensive structure of the magnetosphere, revealing that the Earth's magnetic field interacts with the solar wind to produce a sharp bow shock on the sunward side and a long magnetic "tail" in the shadow.

All the Earth orbiters have incidentally supplied data on the details of the Earth's shape. To a first approximation the Earth is, of course, a sphere. In fact, we know it to be an ellipsoid of revolution, flattened by 21 km in 6378 km at the poles. This ellipsoid is very nearly of the shape which would result from the hydrostatic balance of gravity versus centrifugal effects (The equator, in fact bulges by approximately 200 m too much.) Precise tracking of artificial satellites, however, has now not only confirmed that the Earth is slightly pear-shaped — its southern hemisphere is fatter than its northern — but has also revealed for the first time, a number of other bumps and dips which gravitationally deflect the trajectories of the satellites by small amounts (Plate 21). What is their cause? Are they relics from the Earth's formation? One suggestion is that "highs" may be the tops of the upwelling subcrustal convection cells that cause plate movements. Geophysically such shape measurements offer a new space-age challenge to the planetary scientist studying the Earth, the Moon, and, more recently, Mars, all of which have now been ringed by orbiting spacecraft.

MOON

☾

THOMAS GOLD

The origin of the solar system — our strange and puzzling home in the universe — is not yet understood. There are very many clues, some strikingly clear, others hazy, about the events that must have taken place, about 4500 million years ago, that put together the planets and their satellites, and set them on their orbits. While these clues confine the speculation, they have not yet added up to a clear picture. We still do not know whether it was a strange and unlikely chance that was involved, or whether the millions of other stars like the Sun must all be expected to have similar systems around them. Are the materials we have here the common building bricks for planets in other solar systems? Are there lots of planets with rocks and water and an atmosphere? Is the speculation justified that life is abundant on innumerable other planetary systems?

The scientific space programmes of the US and the USSR were of course designed with an eye on these great questions, and it was clear from the outset that the Moon should be a prime target. Firstly, it was the easiest alien body to reach. Not having any wind or water, erosion would not have destroyed the record of past events. Internal upheavals that shifted, contorted and overturned much of the Earth's surface seemed to have been absent on the Moon — there are no signs of any large distortions in all the many ring-shaped structures. For these reasons there were many guesses that we would find there the geological record that is missing on the Earth, of the earliest periods when these bodies were forming: the geologic record of the solar system, not just one of its bodies.

Now, at the end of the Apollo programme, we have a great deal of information about the Moon. It bears out completely the view that it has a very ancient surface. Very few rocks can be found on Earth that are as old as each one of the lunar ones that were brought back. Nuclear age dating shows that the soil and the rocks became the solids they are between 4½ and 3 aeons ago (one aeon is one thousand million years). 4½ aeons is also the age of the oldest meteorites that have been found, and those in turn show clear evidence of radioactive processes having taken place within them, that could not have persisted for more than a few tenths of an aeon after the same matter suffered the nuclear processing that occurs only in an exploding star. There is good reason, therefore, for considering the time around 4½ aeons ago as the time of formation of the solar system, and the Moon bears evidence that it is not much younger. Its surface is really old enough to contain all the evidence that we are looking for, but if it does, no one knows yet how to read it clearly.

Several quite different possibilities are under discussion at the present time as to how the Moon might have formed. That the Moon and the Earth were formed as one body and were subsequently torn asunder, or that they formed simultaneously from a common cloud of material, is not favoured by the chemical evidence for the Moon. Lunar materials all seem to show marked similarities as a group, and marked differences from the common terrestrial materials. This is so both for abundances of common elements and also for abundances of elements that occur in trace amounts only (Figure 1).

In such theories it would of course be necessary to suppose that the Moon had made its way from a close orbit of the Earth to the more distant one it now occupies, but this is not a problem. One understands clearly how the tides that the Moon raises on the Earth deform the liquid and solid parts of the Earth, and how this in turn causes the Moon to spiral outwards. There are uncertainties in the detailed calculations of the effect, but a time between 5 and 2 aeons would be sufficient to push the Moon out to its present orbit.

Other theories of the formation are the capture of a complete Moon that formed elsewhere, or the capture of many small particles into orbits encircling the Earth, that then accumulated into a single Moon. The capture of a complete Moon is theoretically possible, and there have been detailed discussions how, with the help of enormous tides raised on the Earth during an initial close encounter, such a capture might have been achieved. But even if the capture process is a possibility, it is an extremely unlikely one. A very small range of initial orbits only would lead to capture, rather than to a direct collision with the Earth, or a mere perturbation and escape. One can argue against such a theory on the general grounds that there are some 30 other satellites in the solar system to be accounted for and that capture cannot be used to account for the majority of them. One clearly needs a theory that represents a probable process that would put satellites in orbits surrounding planets.

The accumulation of dust or chunks of material in orbits encircling planets is the most helpful one from this point of view. Saturn's rings give an example that such accumulations can occur, although in that case a little too close to the planet to accumulate in turn into bigger sized objects. Perhaps whenever such rings occurred a little further out from a planet, they did form into satellites in the course of time, and that is why we don't see such rings any more.

In such a theory it is by no means clear that the Moon would have formed directly as a single object, collecting up all the material of the ring. It is quite likely that in the first place many objects would have snowballed in different lanes, and that subsequently, and perhaps over long periods, their orbits were influenced by each other, and by the tides they raised on the Earth, in such a way that they eventually all collided with each other, and that the major body so formed swept up or expelled the remaining debris.

How will lunar observations prove or disprove such theories? How will details of the lunar surface shed light on such processes?

The greatest problem that has confronted the lunar investigators is concerned with basic assumptions. Must one explain how the Moon formed out of the original mix of the elements available in the early solar system? In that case, one has to explain how the chemical sorting occurred within its body, to generate the particular minerals locally, that are now found there. It is known that these minerals do not represent the kind of substance that might have condensed directly in the early solar system, but rather a material that solidified from a melt on some planetary body, and that represents the lighter fraction and thus formed the upper crust. These differentiation processes are well known from the examples on the Earth, and it might therefore be considered that similarly on the Moon there must have been a period of extensive melting and freezing of the rocks. In that case, the evidence of the earlier accumulation processes would also be obliterated there, and only a small amount of late infall would have left its marks on the surface, causing the craters, and crushing up rocks into powder.

The alternative basic assumption would be to suppose that the materials now found on the lunar surface, whatever their chemical composition, represent the last epoch of the accumulation process. After all, one could hardly imagine a planetary surface to give a clearer indication of being shaped by infall than the Moon does. Three-quarters of its area is composed of indefinitely many overlapping craters, with many of them still showing clearly the details expected from the impact of debris of all sizes, falling in at astronomical speeds. Despite a careful search for areas of solid rock, and the selection of landing sites with this search as the prime criterion, no such areas were found. The pieces of rock that were sampled by the astronauts were all, without exception, separate chunks strewn around the lunar landscape (Plate 27), presumably by impact explosions; in no case were the rocks formed or congealed in the locations where they were found. The surface material almost everywhere was found to be a soil composed of a mixture of pulverised rock, just as one would expect of the surface of a body that had accumulated from the infall of solids.

The recent Mariner 10 spacecraft observations of the planet Mercury show its appearance to be remarkably similar to the Moon's (see photos p 14). There are also the same multiply overlapping craters, the same smooth looking low areas, the same patterns of lighter areas surrounding the fresher craters; and very similar dust must cover the surface, since the sunlight is scattered in just the same manner (Plate 22). But the interior of Mercury must be very different from the Moon. It is made of much denser stuff (mean density 5·4 g/cu. cm compared with 3·3 for the Moon) and the temperature

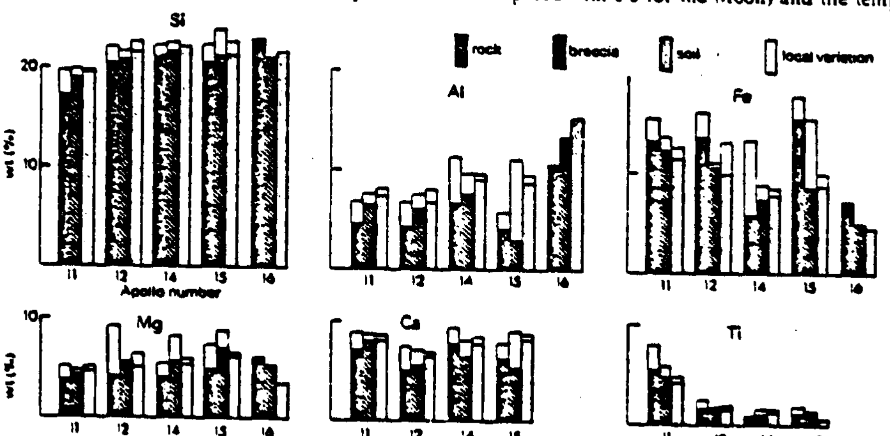


Figure 1 The different landing sites have shown significant differences in the abundances of the elements making up the powdery soil, the compression-welded breccias and the crystalline rocks. The proportions by mass of the six major elements are shown here, for five Apollo landing sites. Oxygen makes up the bulk of the remainder in each case. The abundance of titanium is characteristically higher than in terrestrial samples, and this, as well as several other compositional differences, argues against any common origin of the two bodies. (The data are selected from the chemical analysis teams appointed by NASA)

Figure 2 If a crater excavates material to a depth at which the composition is different, the blanket of ejecta will reflect that fact. (Indeed, studies indicate that there is an inverting effect, with the material excavated from the greatest depth appearing at the top of the new surface surrounding the crater.)

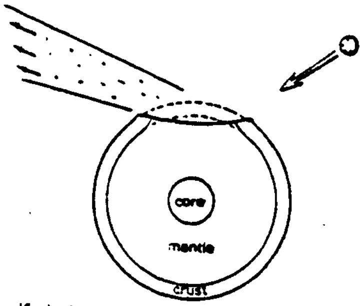


Figure 3 If a body that is differentiated into core, mantle, and crust is hit by a substantial other body, it may lose crustal material only, or crust and mantle, or, of course, it may be shattered altogether. In each case the debris will fill a particular range of orbits only, rather than contribute to a general mix in the solar system. Another body accreting material may thus acquire distinctive layers in succession.

regime in the interior is not likely to be similar. If the Moon's surface was dominated by internally caused effects, combined with only a small amount of later infall, as many investigators think, then would it not be a strange coincidence for Mercury's surface to match it so closely? On the other hand, if these are the surfaces that result from infall only, then one merely has to suppose that the interior circumstances did not have a large share in shaping the outside of either body.

But what can be said about the chemical composition of the Moon? Can one prove that it was locally melted and chemically rearranged, or could these processes have taken place elsewhere and earlier, so that already modified material came to fall in and form the outer layers of the Moon?

One can certainly prove that there has been some melting on the Moon. Many rocks that were brought to Earth are crystalline, clearly frozen magmas. But then such rocks would be expected to be made in the course of an impact history in any case. The largest impacts, such as made the huge circular basins on the Moon, must have generated pressure waves of such intensity that a depth of many kilometres of molten rock would have been generated over the area of the basin. Much later, when an overburden of debris had accumulated over the frozen magmas, some other impacts would dig down and keep bringing samples of this material up to the surface.

But would simple infall not have provided a uniform material covering the entire Moon? Perhaps some large pieces that fell in may have had their individuality, but surely the huge amounts of small particles must have coated the Moon with a uniform mix. How can the Moon end up with as much regional variation in the chemical composition as was discovered? (Plate 24.)

Each time a large impact generates a huge basin, material is excavated from a great depth and thrown over the surrounding areas. Mare Imbrium, for example, was probably dug down to a depth of 150 km at the instant of the gigantic impact. If any chemical differences existed vertically from the process of building up the Moon, then those are converted into horizontal variations by such an event (Figure 2). Vertical differences can of course result when different types of material became available at different times during the infall periods.

Could the chemical processing of the lunar materials have happened elsewhere before they built up the Moon? Nothing that we have learned so far is able to rule this out. Meteorites that we find give clear evidence in many cases of being debris of smashed up planetary bodies. Some of those bodies must have been hot enough for much material to have been melted. Differentiation processes similar to those that happened on the Earth must have happened on these parent bodies. One class of meteorites has indeed a composition that is quite similar to that of the surface of the Moon, although not absolutely identical with it. So here also there is no clear-cut answer to the dilemma. What meteoritic debris from what particular parent bodies populated the orbital lanes that made the last addition to the Moon is a very difficult matter to assess. The meteorites we now find represent only a tiny fraction of the material that was once there to build the planets, and it is just the material that remained by chance on orbits not yet swept up by the major bodies. Many other classes of meteorites might once have existed or still exist, but we do not know them because they have already been swept up, or because the Earth does not happen to intersect their orbits at the present time. Thus, the meteorites also do not give a clear answer. Chemically differentiated material is common among them now, and may have been common in the early times. Debris from early collisions must have had a distinctive chemical composition in each case, and would have been scattered onto particular orbital lanes, which were then swept up in some arbitrary order by the final bodies (Figure 3).

We are thus left with the basic problem that must dominate the entire discussion. Is the detailed lunar chemistry the result of lunar processes, or the result of the final stages of the building of the Moon? Are we looking at an Earth-like body that obliterated the record of its formation process, or are we looking at that record but, because of its complexity, failing to understand it?

If neither the chemical composition nor the overall appearance can give a clear answer between these alternatives, what other evidence is there to look to? The subsurface structure can be deduced to some extent from the study of the very faint moonquakes that are recorded, and also from the seismic signals resulting from occasional meteorite impacts and from the impacts of abandoned spacecraft. Also, radar and other radio-frequency methods can be used for depth sounding of the lunar ground. If the chemical differentiation had occurred on the Moon, then one would imagine that a layer of bedrock of frozen lava would generally lie underneath the dusty surface. The dust would only be a coating derived by the pulverising action of large and small impacts. On that basis, the flat floors of very many large craters, and of the low-lying areas, are thought to be the lava beds. On the other hand, if the surface represents the build-up of material from infall, powder in various stages of compaction may extend to a depth of many kilometres.

The seismic signals show the Moon to be totally different from the Earth. Firstly, it is internally about 1000 times quieter: moonquakes are weak and rare.

This of course fits well with the observation that the surface shows little evidence of distortion. The second big difference is that internally caused moonquakes come frequently, and perhaps predominantly, from a very great depth, approximately halfway to the centre of the Moon: that is, a depth between 700 and 1200 km. On the Earth the great majority of 'quakes originate shallower than 60 km and only very rarely have 'quakes been recorded from as deep as 700 km. It is thought that deep earthquakes are rare because the deep material is hot enough to flow plastically under stress rather than to break suddenly; this would suggest that the Moon is cooler inside.

The nature of the seismic signals on the Moon proved to be most remarkable and quite different from those that occur on Earth. Here an impact or an explosion 100 km away would generally produce a characteristic sharp "first arrival" signal after perhaps 20 seconds, followed by the slower transverse waves, with the whole signal being over in not much more than a minute. On the Moon, in the same circumstances, a noisy signal builds up slowly, with no very sharp beginning, takes between 5 and 10 minutes to rise to maximum amplitude, and then about 1 hour to fade away (Plate 23).

What can be so different on the Moon? On the Earth there is almost everywhere a solid sheet of bedrock that propagates the seismic signal. This is evidently not the case on the Moon. Those who believe that bedrock is present have to say that it is heavily smashed up and fragmented in a way that it never is on the Earth, so as to create a slow and reverberant transmission medium. The alternative, very acceptable for the interpretation of the seismic data, is that a soil, like that found on the surface, exists to a depth of several kilometres, gradually or abruptly increasing in compaction with depth due to the weight of overburden and the hammer blows of earlier meteorites.

Earth-based radar gives a clear indication that there is not a sudden transition from the top soil to broken-up bec[illegible] at a shallow depth. Long-wave radar (at a wavelength of 7·5 m) would penetrate through the material of the top soil and show subsurface reflections down to a depth of at least 100 m and quite possibly 200 or 300 m. (Lunar soil is much more radar transparent than any terrestrial soil or rock.) Jumbled up pieces of rock would scatter the radio waves back with an intensity several times greater than is observed. Moreover, this rough subsurface would make the Moon more or less equally reflecting over the whole disk, just as the rough optical surface makes the full Moon more or less equally bright. The long-wave radar, however, shows the edge to be more than 100 times fainter than areas closer to the middle. The radar Moon is enormously limb-darkened. It is clear that there are no large areas on the Moon where a thin layer of the surface soil overlies coarsely broken-up bedrock. The alternative explanation of the seismic signal, in terms of deep deposits of a powder variously compacted, would agree with the radar data. So this evidence fits much better with the cold accumulation theory of the surface, than with the lava origin. The fact that no bedrock could be found in any of the Apollo missions would then also have a natural explanation.

Some investigators believe that the mere presence of big flat areas is sufficient to prove that huge lava outpourings have taken place. They also believe that some individual features represent the flow patterns of lava, or the outcrops of lava sheets on steep slopes. Comparable photography of areas of the Earth that are free from vegetation would have left no doubt about the existence of many lava flows. The lunar evidence is not nearly so convincing. Apparent "flow fronts" of supposedly congealed lava (Plate 25) are seen on the flat ground and are regarded by some as convincing. On the other hand, entirely similar flow fronts are seen around the base of very many remains of old crater rims, and for them nothing other than a surface erosion and transportation process, albeit it of unknown nature, can be invoked (Plate 26). On a time scale of 4½ aeons, very minor processes can have been sufficient to cause quite large changes in a dusty surface. It is very difficult to be sure what moved the dust, although various electrostatic processes would seem perfectly adequate; but it is equally very difficult to be sure that no surface migration of dust could have taken place. Another feature claimed to represent bedrock at a shallow depth is an apparent ledge photographed by the astronauts when they looked across to the other side of the valley called Hadley's Rille. Again, this evidence is not very strong. The ledge was not sampled, and may well represent no more than a stratification in compaction of the powder. Compacted powder will give an appearance of fracture lines and planes that can be very similar to solid rocks, even though the forces necessary for the fracture may have been orders of magnitude smaller. On the opposite side of the argument we have the very many craters that are of quite remarkable perfection, being accurately round with a perfectly smooth bowl as the interior surface, and an absolutely level rim (Plates 30, 31). Many of those are in the size range from tens of metres to kilometres. A sheet of brittle rock breaks into much more erratic patterns.

There are many other lines of evidence that one can pursue. The slight variations in the local strength of gravity (Plate 28), measured through the perturbations of orbiting spacecraft, revealed the existence of the so-called "mascons", regions of higher density evidently underlying the large, flat-bottomed basins. Such a mascon requires the ground at a depth between ten and a few hundred kilometres to be quite strong, for otherwise the region would have sunk deeper in the long time since its formation. If huge amounts of lava had been poured out, one would suspect the ground just beneath to have been partly molten, and no rocks would then have the required mechanical strength. There is a great problem here with that explanation, while in terms of a basin subsequently filled by surface deposit, there is no need to think that the deep ground could not have been cool enough at all times.

Each of these many points can be debated, and the answers are not yet sure. Just as was the case in the early days of geological investigations of the Earth, one has a great deal of knowledge of facts, but as yet very little basic understanding. What we have seen is that the Moon is dramatically different from the Earth, and that we must therefore argue out each case from first principles and not by analogy with terrestrial investigations.

The next step must be to find a clear way to decide between the two basic possibilities discussed here. If the Moon is a locally differentiated body, as many investigators believe, the information it can provide is limited in much the same way as the Earth's. However, if its surface material represents the last infall, the evidence it then provides is perhaps unexpected; but a possibility must not be rejected just because it would teach us something we had not foreseen. In that case, we would hope to learn a great deal from the Moon about the early solar system and the construction of the Earth and the other planets.

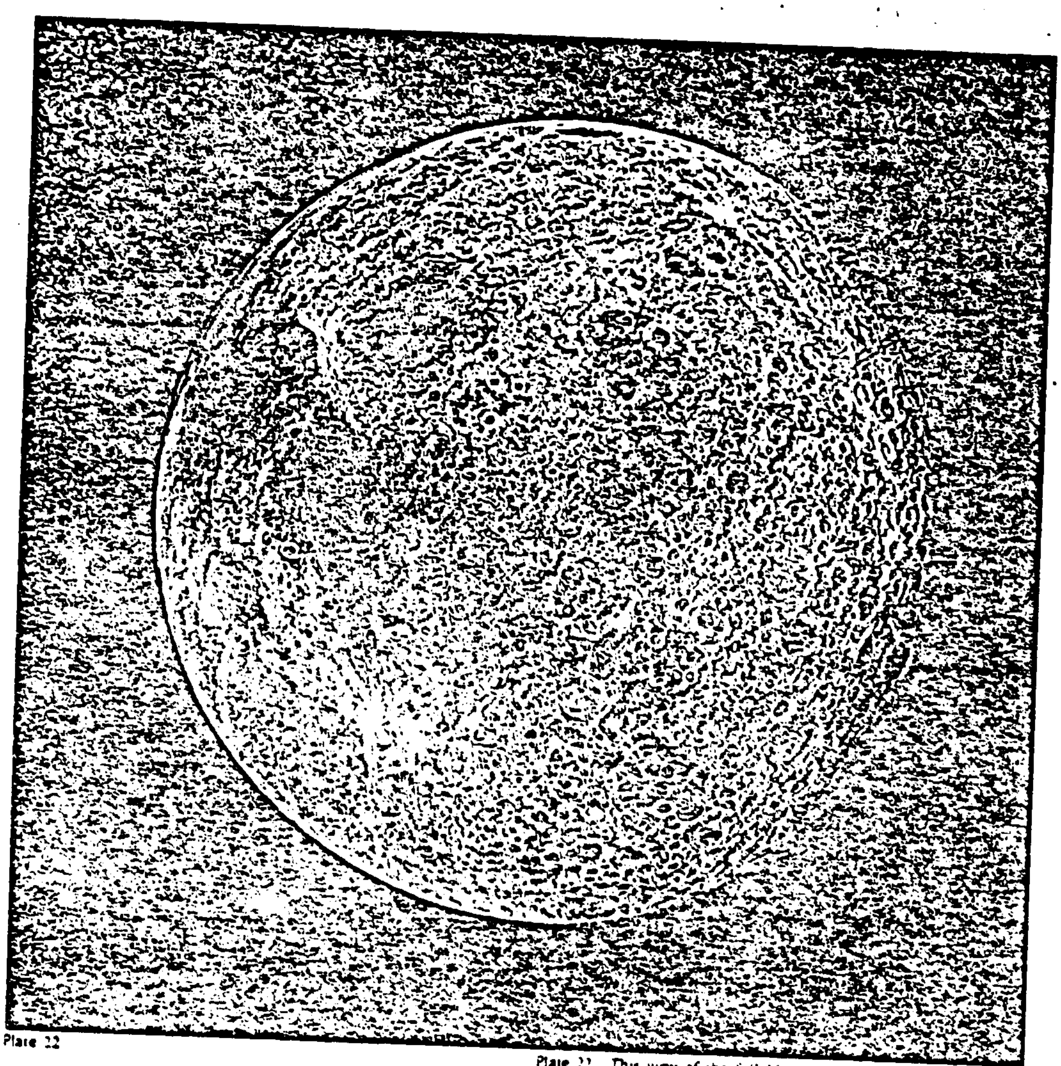


Plate 22

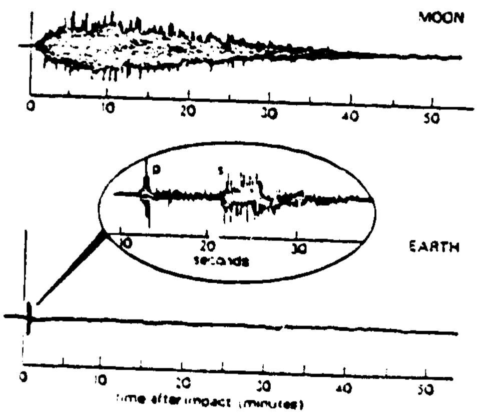


Plate 23

Plate 22 This view of the full Moon, taken as the Apollo 17 crew began to head for home, shows a large part of its far side. The striking similarity between the lunar surface and that of Mercury (see Figures 2 and 3 on p 14) argues for the treatment of the two surfaces having been alike. If both surfaces were mainly shaped by external effects, this similarity would be expected. The interiors, however, are likely to be quite different, and any volcanic activity would be expected to have been markedly different (in nature, extent, and timing of occurrence with respect to infall) for the two cases

Plate 23 Lunar seismic signals are very different from those on Earth. The signal shown in the top trace, from an impact approximately 100 km away (Apollo 12 seismic experiment), rises slowly and reverberates for one hour. In similar circumstances on the Earth the signal would have been almost all over in less than two minutes, while the lunar one has only just begun to rise. This great difference must mean the absence on the Moon of the good direct path for the sound provided on the Earth by solid coherent rock, and instead a sound propagation channel of very unusual properties: it must conduct sound much slower than solid rock; it must scatter sound waves to cause the reverberation; it must duct sound waves under the surface so that the energy is not lost too quickly by transmission downwards; and the dissipation of sound waves must be very low. A deep layer of compacted powder or thoroughly smashed-up rock have been discussed for this. (After G. V. Latham and others, Science, vol 167, p 455)

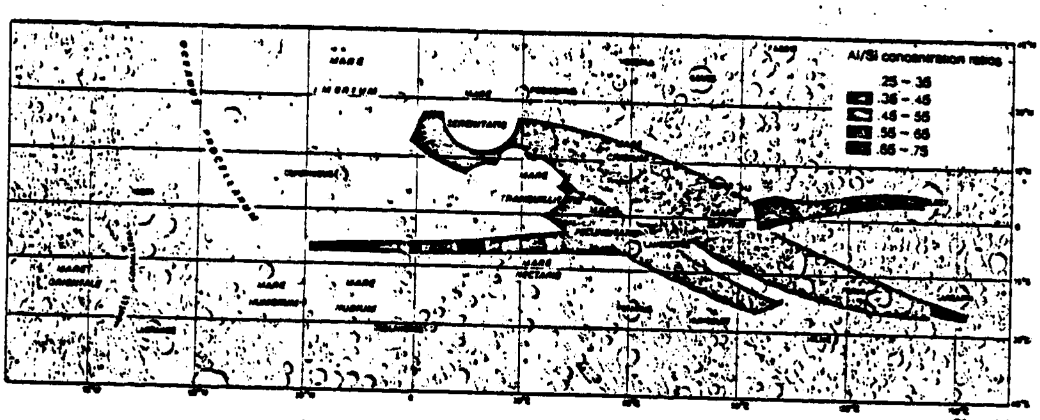


Plate 24

Plate 24 While the Apollo command module was in orbit around the Moon, instrumentation aboard it scanned the lunar surface for any X-ray fluorescence it might be exhibiting. The X-ray energies were analysed to identify the chemical elements in the surface materials. The swath across the Moon which the orbital telescope examined showed the aluminium-silicon abundance ratio (in the top few millimetres of the surface) to have marked regional variations, aluminium being generally more abundant on the high ground. Greater uniformity was observed with respect to most other elements. (Diagram from Proceedings of the Fifth Lunar Science Conference Geochimica et Cosmochimica Acta, Supplement 5, Pergamon Press, in press.)

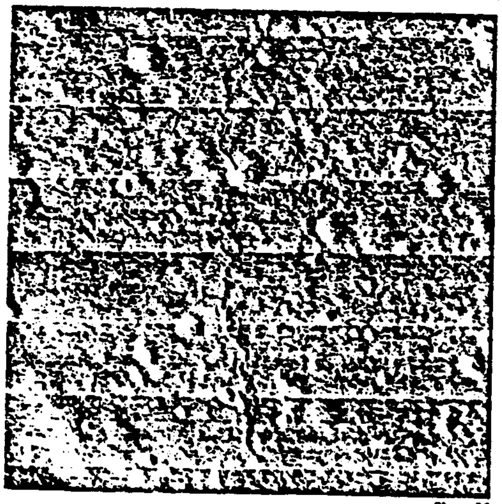


Plate 25

Plate 25 A "flow front" that has been interpreted as a lava flow arrested by freezing. It is on flat lunar ground, and the step is a few metres high. The way in which craters in the flow front are engulfed but not filled casts doubt on any genuine liquid as being the flowing medium. Craters appear to be merely coated by the "flow", and the general cratered surface looks much the same on both sides of the front (NASA Lunar Orbiter photo)

Plate 26 An area of flat "mare" surface from which protrude some old and heavily eroded mountains. At the base of each mountain the junction line with the mare ground has a characteristic profile — a "shoulder" — which must represent material that has been moved downhill and accumulated in this peculiar fashion. Some of these "shoulders" have a very similar appearance to the "flow-fronts" of Plate 25 especially in the manner in which they engulf small craters (NASA Lunar Orbiter photo)

Plate 26

Plate 28 Gravity map showing mass excess and mass deficiency over lunar surface.

This information comes from the very precise observations of the orbits of spacecraft.

The map shows that the large circular basins represent a mass excess ("mascons"), despite their lower surfaces. Denser material must underlie them. Mare Orientale, the large feature on the left, which lies on the reverse side of the Moon, is a basin without much filling, and shows the features left by the gigantic impact. If it received a surface fill like the other circular maria, it would show the same positive gravity anomaly as they.

Density differences on this scale need not be due to differences in composition. The lunar ground may well be porous, as it is near the surface, to depths of many tens of kilometres, before the weight of overburden would crush out all porosity. The floors of basins have been subjected to the large pressures at the impact, and they will not have retained any porosity below. A basin with a denser floor and a surface fill of one to three kilometres would produce the observed effect.

Small craters are negative gravity anomalies, corresponding to the excavated material. (Diagram from Proceedings of the Fifth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 5, Pergamon Press, in press).

Plate 27

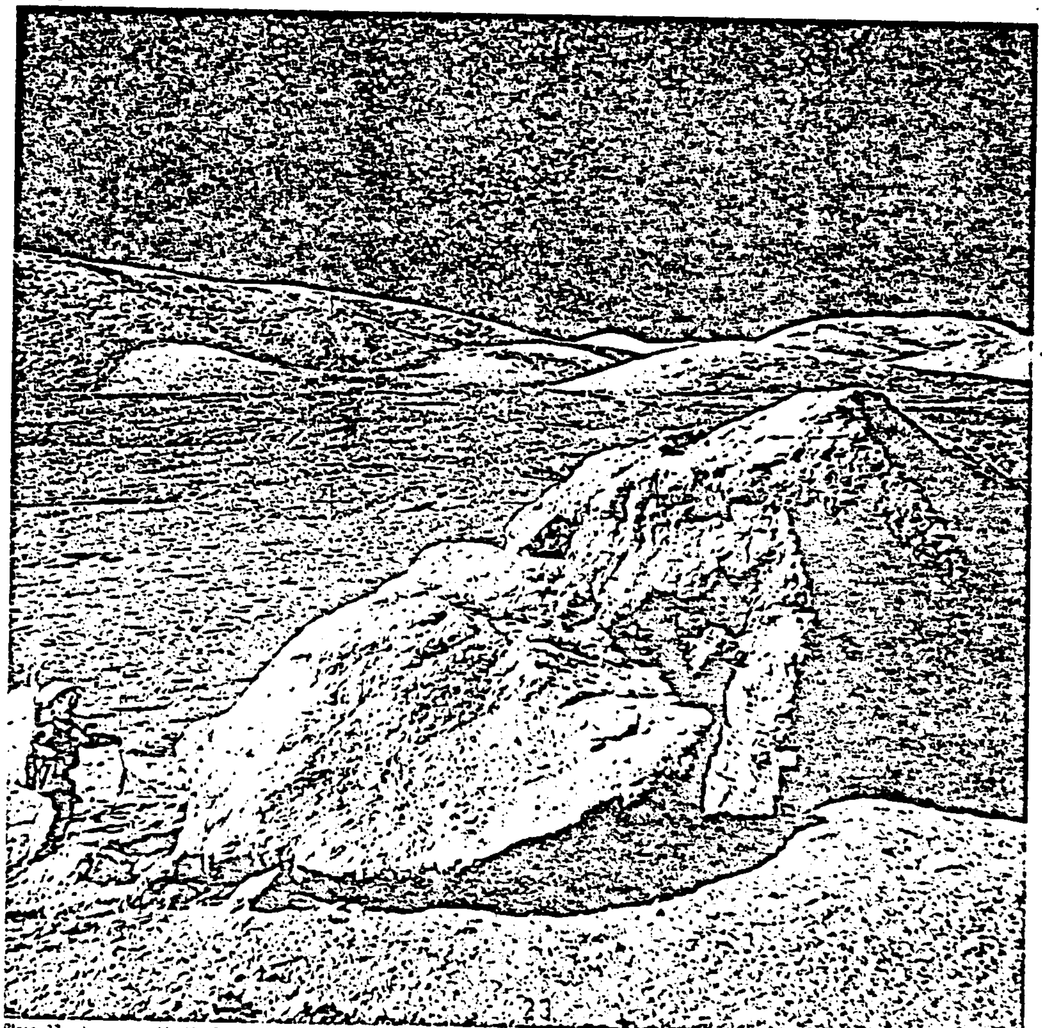
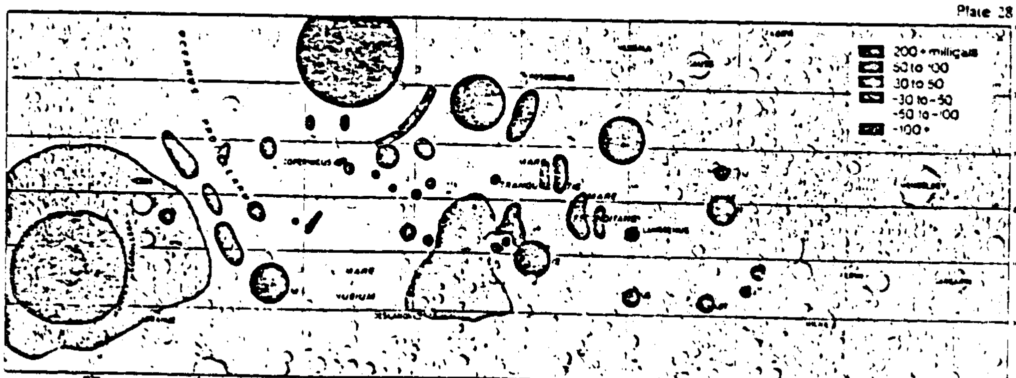


Plate 27 Astronaut H. H. Schmitt next to a large split boulder. Rocks encountered by the astronauts or photographed by the remote-controlled lunar orbiters were always found as separate pieces strewn over the surface and usually partly embedded in the dusty soil. They appear to have been tossed to their present positions by impact events. No identification of crystalline rocks frozen in the place in which they now are, was made in the course of any of the Apollo landings (Apollo 17 photo)

Plate 28



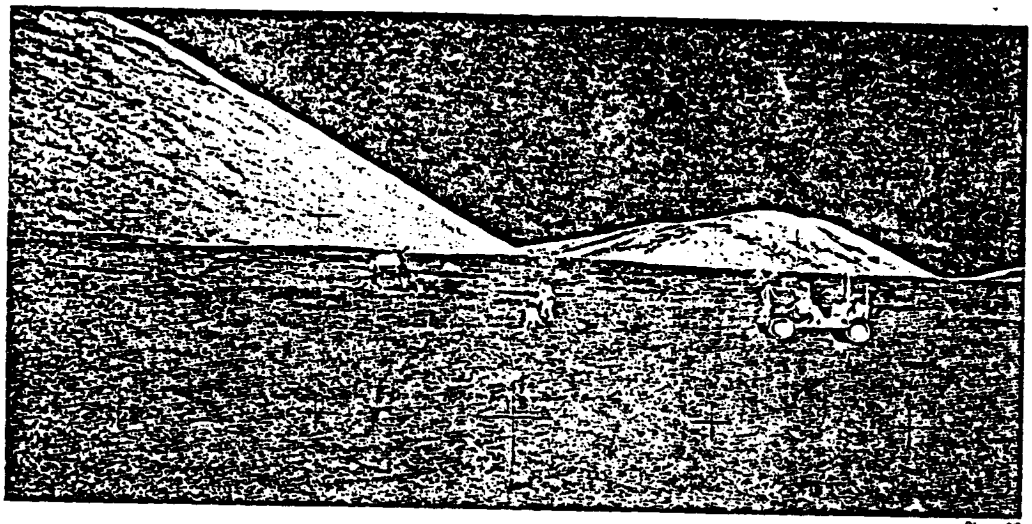


Plate 29

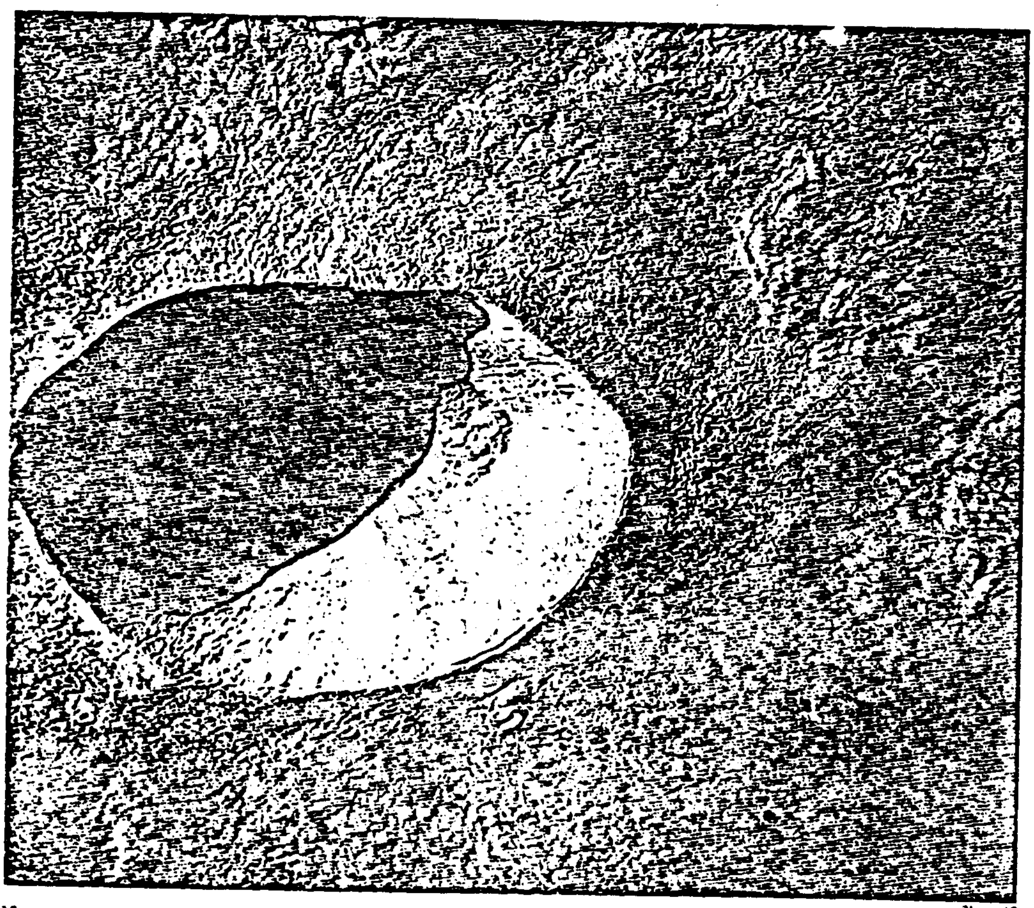


Plate 30

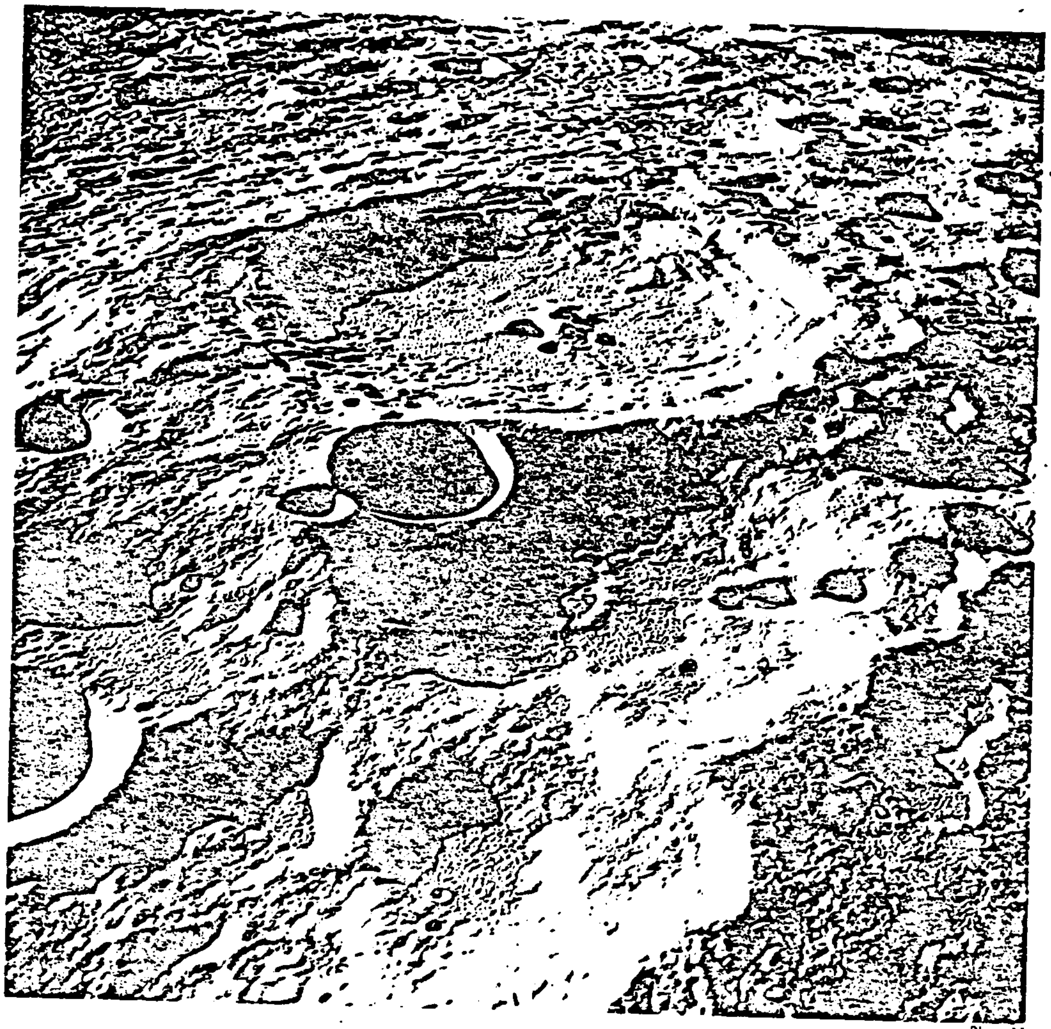


Plate 31

Plate 29 Astronaut Jack Schmitt at work at the Apollo 17 landing site in the Taurus-Littrow area of the Moon. The background consists of the South Massif and Family Mountains

Plate 30 Crater Schmidt, seven miles across, lies on the western edge of Mare Tranquillitatis (Photo: NASA, Apollo 10)

Plate 31 The crater seen here, International Astronomical Union 308, lies on the lunar far side. It is some 50 miles in diameter. Smaller craters testify to the good circularity displayed by many lunar impact features. This and the preceding photograph of crater Schmidt confirm that many craters are remarkably perfect circular bowls. Impacts in rocks usually generate shapes that show more pronounced fracture patterns, and solid rocks underneath powder would result in ledges and steps in the interiors of craters (Photo: NASA, Apollo 11)

Plate 32 This thin section micrograph of an Apollo 11 sample of lunar rock proves that some of the Moon's material, at least, is crystalline. The different colours are here produced by polarised light; several different minerals can be distinguished. The photograph was taken by Dr Klaus Keil of the University of New Mexico

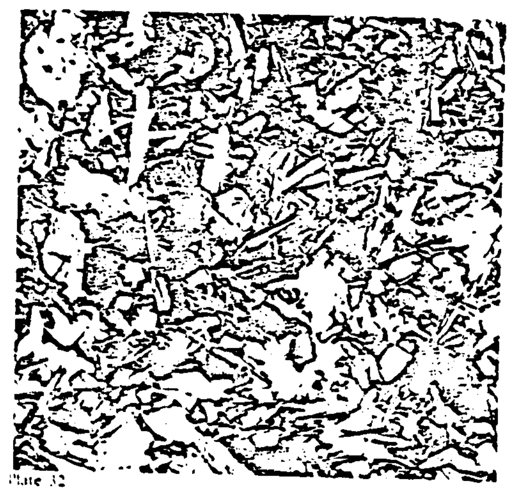


Plate 32

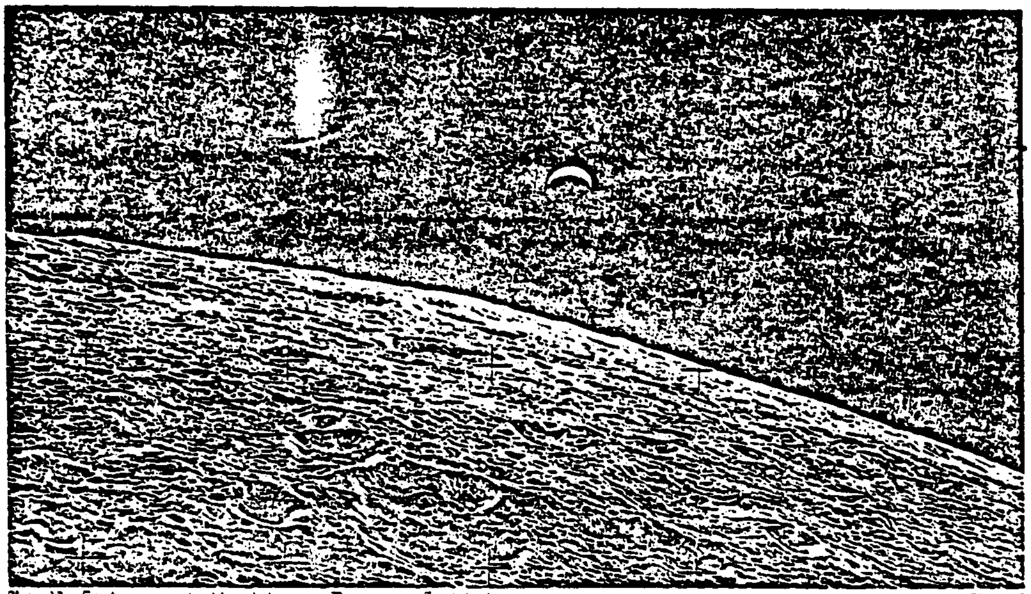


Plate 33 Earthrise over the Moon's horizon. The crescent Earth had never been glimpsed before man landed on the lunar surface. This spectacular photograph was taken during the Apollo 12 mission

Plate 33

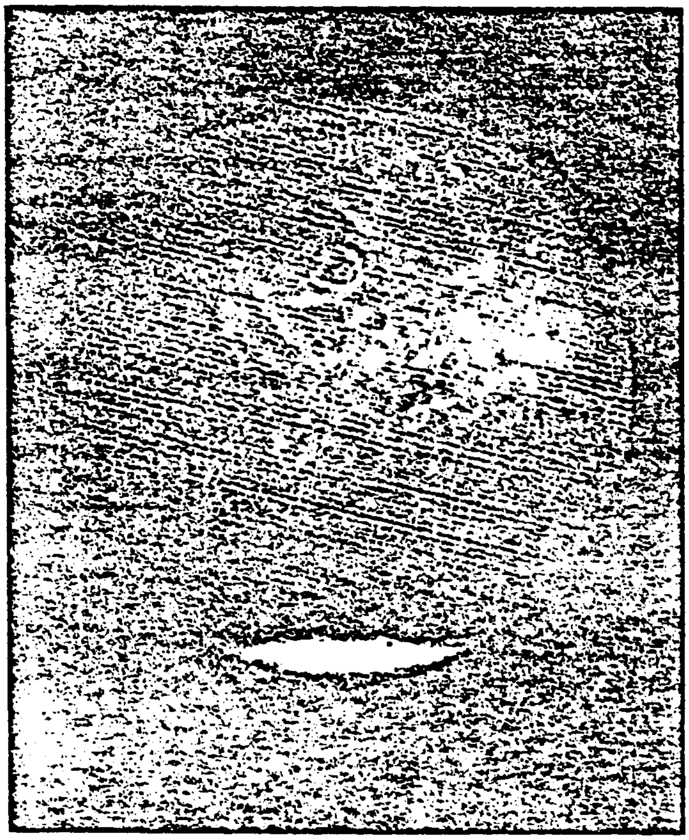


Plate 34

Plate 34 Mars photographed by Mariner 7 in August 1969. The south polar cap is at the bottom of the picture, bright ring-shaped object is the giant volcano Olympus Mons

Plate 35 A Martian channel in the central highlands. Many tributaries and a highly sinuous course characterise this type of channel

Plate 36 A great mass of chaotic terrain with a channel that flows into the northern lowland

Plate 37 A Martian sand dune field that is about 50 km across

Plate 38 The great equatorial fault valley with its diagonal subsidiary valleys. The valley is about 75 km across and 6 km deep


Plate 35

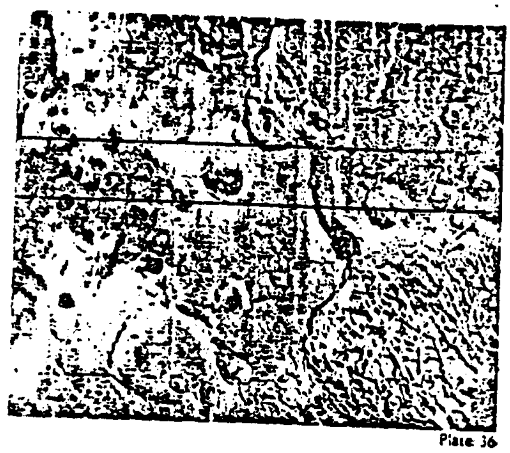


Plate 36

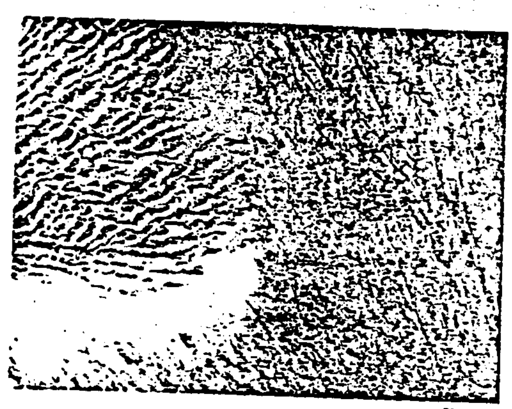


Plate 37


Plate 38

Plate 39

Plate 40

Plate 39. Photograph taken late in the Mariner 9 mission of the north polar ice cap and the dark ring around the cap. High-resolution pictures show the "etch pits" lie in the dark ring.

Plate 40. Photograph of layered deposits near the Martian south pole. The closed depressions are the so-called "etch pits" eroded by the wind.

Plate 41. Map of Mars compiled from about 1500 Mariner 9 pictures at a scale of one to fifty million. The bright and dark markings are derived from Earth-based telescopic photographs of the Planetary Patrol, Lowell Observatory. (Redrawn from US Geological Survey 1973 map)

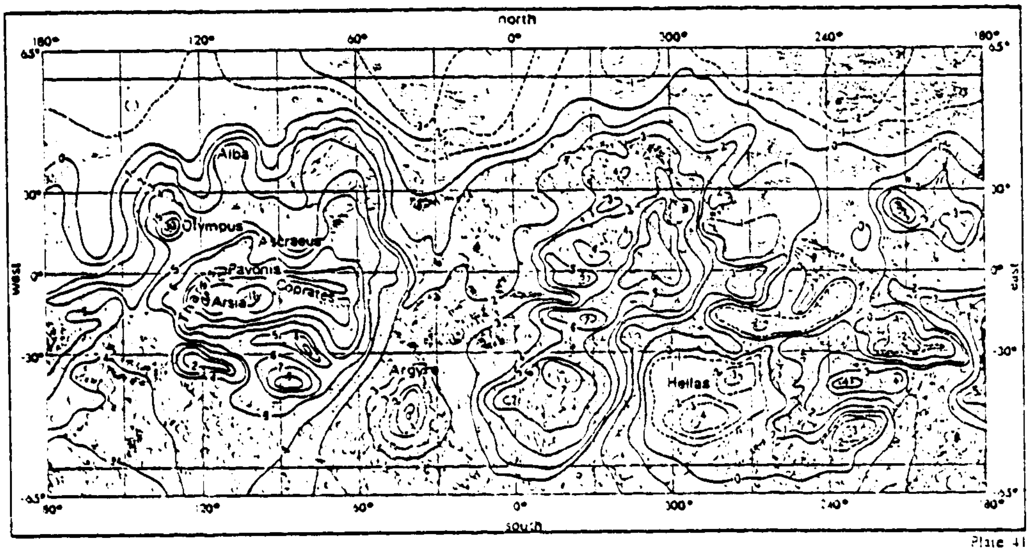


Plate 41